EMISSIONS FROM COMBUSTION TECHNOLOGIES WITH A FOCUS ON BRICK MAKING AND IN-HOME COOKING

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THESIS

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ABSTRACT

Emissions from seventy household stoves in Tibet and Nepal and thirteen brick kilns in South Asia were measured to quantify aerosol and gaseous pollutant emissions, including particulate matter ($PM_{2.5}$), carbon monoxide (CO), carbonaceous particles, and optical scattering and absorption. In addition, a pilot study was conducted of small-scale industry emissions from a restaurant, candy making operation, and two pottery kilns.

Emission factors from household stoves were compared across fuel types, stove characteristics, and study region. Stoves measured in Nepal emitted more black carbon when sugarcane was used in the fuel mixture. Chimney stoves had better combustion efficiency and lower emissions than non-chimney stoves and wood fuel produced significantly less $PM_{2.5}$ and CO compared to dung fuel in Tibet. Overall, Tibetan stoves had higher emission factors compared to stoves in Nepal or Honduras.

Small-scale industry stoves, restaurant and candy making, had similar emission factor magnitudes and particle properties to household stoves. Unlike stoves, the traditional straw pottery kiln had high carbon monoxide emission factors and almost no black carbon emissions (5% of $PM_{2.5}$). Conversely, the wood pottery kiln had a much higher percentage of black carbon (78%). In comparison, household stoves in Nepal averaged 22%.

Measurements in the exhaust of six brick kiln technologies demonstrate differences in overall emission profiles and relative climate warming resulting from kiln design and fuel choice. Emission factors differed between kiln types, in some cases by an order of magnitude. The brick kilns currently dominating the sector had the highest emission factors of $PM_{2.5}$ and light absorbing carbon, while improved Vertical Shaft and Tunnel kilns were lower emitters. An improved version of the most common technology in the region, the zig-zag kiln, was among the lowest emitting kilns in $PM_{2.5}$, CO, and light absorbing carbon. Emission factors measured here are lower than those currently used in emission inventories as inputs to global climate models; 85% lower ($PM_{2.5}$) and 35% lower for elemental carbon (EC) for the most common kiln in the region, yet the ratio of EC to total carbon was higher than previously estimated (0.96 compared to 0.47). Total annual estimated emissions from the brick industry are 120 Tg CO^2, 2.5 Tg CO, 0.19 Tg $PM_{2.5}$, and 0.12 Tg EC.

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Chapter 1

Introduction and research objectives

Emissions of gases and particles from combustion have health, air pollution, and global climate impacts. Combustion of some fuels, such as biomass and coal, tend to produce higher levels of pollutants compared to cleaner fuels such as liquid petroleum gas (LPG) or methane. These high emitting fuels are used for cooking, heating, and industrial energy needs in most of the developing world. The aim of this study is to directly measure emissions from two major emission sources, household stoves and brick production, in order to quantify the magnitude of the emissions and understand the variability within each sector.

The pollutants measured are discussed first, followed by the climate impacts in Section 1.2. Cookstoves are introduced in Section 1.3, and South Asian brick kilns are introduced in Section 1.4.

1.1 Pollutants of interest

Emissions of Carbon Monoxide (CO), Carbon Dioxide (CO_2), particulate matter ($PM_{2.5}$), organic carbon (OC) and elemental carbon (EC), and aerosol optics were measured for all sources in this study. CO_2 is produced from complete combustion and is a greenhouse gas. Most other species emitted are products of incomplete combustion, many of which have both health and climate impacts.

1.1.1 Carbon monoxide

The amount of CO emitted from a fuel depends on the combustion conditions. CO is usually the second greatest gas emission from combustion, with the first being CO_2. It is produced when there is insufficient energy or oxygen at the microphysical level to produce CO_2.

CO is one of the 6 criteria pollutants established by the U.S. EPA, National Ambient Air Quality Standards (NAAQS) because of health impacts due to exposure. The maximum allowable exposure is 9 ppm for 8-hrs. Inhalation of CO causes a reduction of available oxygen in the body and has the greatest effect on the brain and heart. At high concentrations, it can cause unconsciousness or even death. Chronic exposures to non-lethal concentrations is often undetected or misdiagnosed [23]. Symptoms include dizziness, nausea, confusion, and depression. Chronic exposures has been correlated with increased incidence of heart disease. CO exposure is particularly dangerous for pregnant woman; CO crosses the placenta and can cause low birth weights and brain damage [23].

CO also has an indirect warming effect on climate. The CO molecule doesn't absorb significant amounts of solar radiation, like green house gases. However, reactions in the atmosphere have a warming effect. It contributes to tropospheric ozone production, a climate warming species or it can combine with OH to produce CO_2. CH_4 is another green house gas that is more warming that CO_2 by mass that also reacts with OH. CO reduces the concentration of OH in the atmosphere, and thus extends the lifetime of CH_4 [41].

1.1.2 Particulate matter

$PM_{2.5}$ refers to the mass of particles that are smaller than 2.5 micrometers and is composed of carbonaceous, inorganic, and mineral species. Inhalation of small combustion particles is a well-known health hazard, largely because of research done on cigarette smoking. Both health and climate effects are caused by $PM_{2.5}$.

1.1.3 Organic and elemental carbon

Carbonaceous emissions from biomass combustion can be categorized as organic carbon or black carbon (BC). Carbonaceous particles are known to have an impact on the climate due to several mechanisms. The most direct is particle interaction with solar radiation; light is either absorbed and causes warming or is reflected, causing a reduction in the solar radiation that would have otherwise remained in the earth system. Other climate effects, both warming and cooling, are caused by particle influence on cloud formation and cloud lifetime, and changes in snow and ice albedo. Considering all known climate effects and uncertainties, OC has an overall cooling effect on the climate, and BC has a warming effect [6]. Biomass combustion releases a mixture of BC and OC that may cause either warming or cooling depending on the ratio of these species emitted.

Elemental carbon is the term given to BC that is determined using the thermal optical analysis (TOA). This distinction is made because there are known, but not necessarily quantitatively understood, differences from true BC mass using this method.

1.2 Metrics of interest

The concentrations of pollutants need to be in a form that is relevant and useful to other researchers. In this study, several metrics are used. Emission factors are in mass of pollutant per fuel mass, and can be used to estimate total emissions given the fuel consumption. Similarly, scattering and absorption that is related to the fuel consumption in m^2/kg fuel can be used to estimate the direct climate effects of a source. The ratios of optical properties and carbonaceous particles, indicate the warming or cooling potential of particle emissions.

1.2.1 Optical absorption and scattering

OC predominately scatters and EC predominantly absorbs light, yet the amount of scattering per mass of OC or absorption per mass of EC is not constant. Thus, the optical characteristics of the particles were also measured. Optical measurements can quantify the light scattering or absorption by particles per volume of air, but cannot be directly related to mass. Both TOA and optical measurements are required to obtain the most complete understanding of the climate impacts of particles.

1.2.2 Particle properties

Particles can warm or cool the atmosphere depending on their composition. Two measures indicate the nature of particle emissions. Single scattering albedo (SSA) is the ratio of scattering to extinction. A SSA greater than roughly 0.6 - 0.8 is a cooling mix of particles, whereas below that value is warming [17]. The ratio of EC to total carbon (EC/TC) also indicates how much absorbing material is in the particles. It also describes the combustion because EC is made only in flames, while OC comes from unburned fuel escaping primarily during smoldering combustion.

The Absorption Angstrom Exponent (AAE) is a metric that quantifies the wavelength dependence of absorption. Particles, such as black carbon, that absorb light equally over a range of wavelengths have an AAE of 1 [3]. Previous measurements of AAE in biomass stoves are in the range of 1-5 [32]. The equation for AAE is discussed further in Section 2.2.3.

1.2.3 Emission factors

An emission factor (EF) is an amount of a pollutant relative to an activity metric, such as energy or fuel consumed. Emission factors are used to estimate the emissions from individual sectors. For example, an estimate of the emission factor for particulate matter of diesel trucks (g PM/kg diesel) can be multiplied by the amount of diesel used by the total truck fleet, resulting in the total PM emissions from diesel trucks. This framework is used to compare the amount of pollution from different sectors and, where regional fuel use data is available, to understand how emissions vary by region. In this study, emission factors in grams of pollutant per kg fuel burned are reported for $PM_{2.5}$, CO, EC, and OC. For optical measurements, emission factors of absorption and scattering are reported in m^2/kg fuel. The optical emission factors are used to estimate the climate forcing due to individual sectors.

1.3 Climate impacts

Both cookstoves and kilns emit species that influence climate such as CO_2, CO, and short-lived climate forcers (SLCFs) such as aerosols and methane. It is often believed that biomass burning is CO_2 neutral; that is, CO_2 released from combustion is quickly reabsorbed back into the ecosystem with new plant growth. However, biomass burning, including combustion in cookstoves, may not be neutral with respect to climate impact. Poor combustion quality leads to products of incomplete combustion (PICs) that have a greater impact on the climate impact per molecule compared to CO_2. In addition, sustainable harvesting, balancing consumption with regrowth, may not be practiced [39].

In order to predict global climate change impacts, emissions of co-emitted species must be considered. Warming and scattering particles such as BC, OC, SO_4, and global warming gases all need to be quantified in order to understand the climate impact of an emission source.

A comparative analysis of greenhouse gas emissions from various fuel types used in cookstoves shows that dung emissions have greater climate warming than either agricultural waste or wood even when sustainably harvested. In comparison, fossil fuel stoves using kerosene or liquid petroleum gas (LPG), produce less greenhouse gas emissions per energy transferred than any biomass fuel [39].

1.3.1 Short-lived climate forcers

BC is second only to CO_2 as a source of positive radiative forcing, contributing 1.1 W/m^2 (0.17-2.1 W/m^2) to the atmosphere [6]. BC has an atmospheric lifetime of about a week and as a result, atmosphere concentrations quickly decrease when emissions are reduced. This is unlike most greenhouse gases, including CO_2, where current emissions have a lifetime of approximately 130 years [40]. The combination of strong positive forcing and a short climate lifetime makes BC a species of particular interest for climate-driven emission reduction polices.

In some cases, the warming effect of particles does not end after deposition. Particle deposition onto snow and ice lowers the surface albedo and contributes to enhanced rates of melting [10]. Because the albedo of snow is higher than most particles, even particle mixtures with high OC to BC ratio lower the snow albedo, and thus have a climate warming effect.

The Himalayan glaciers have greater rates of particle deposition compared to other global ice sheets because of the close proximity of dense populations and polluting sources. Biomass burning is a significant contributor to short-lived climate forcers that are transported in the Himalayan glaciers, primarily in the pre-monsoon periods [5]. BC deposition in the Himalayan glaciers is estimated to be 900-1300μgm^{-2} in the pre-monsoon season and most is transported from India and Nepal [51].

On a global scale, the emissions from of household biomass combustion is substantial; residential BC emissions from cooking and heating contribute 25-33% of total global atmospheric concentrations [6]. In Asia, residential emissions dominate other regional emission sources, contributing about half of the total $PM_{2.5}$ emissions, 60% of EC emissions, and 85% of OC emissions [53].

1.4 Introduction to biomass burning for household energy

In the developed world, most of our energy needs are met by centrally located electrical power generation, where pollution is monitored and controlled at point sources. However, electricity access in the developing world is poor; 28% of households have no electricity in developing countries and many more have insufficient access to meet their energy needs [43]. In the "least developed counties", as defined by the United Nations Development Program (UNDP), 79% of household have no electricity and 91% lack access to modern household fuels [43]. The energy demand is met with biomass that are combusted for heating, cooking, and lighting. Pollution from these sources is not controlled, monitored, or quantified.

1.4.1 Cooking and heating fuels

Solid fuels used for cooking and heating include wood, agricultural waste, dung, charcoal, coal and even garbage. These fuels can vary greatly in size, type, and moisture content and all of these variables can affect pollutant emissions. Cooks generally choose fuels that have the greatest energy efficiency that they can afford, though other factors such as cleanliness, time costs, and risks may play a role in fuel choice. An instructive framework for considering cooking fuel choice is the energy ladder, where fuels of higher value are higher rungs and lower value are lower rungs. It general, dung and agricultural waste are lower valued fuels, wood is higher, and gas and electricity are higher yet. Lower pollutant emissions are generally associated with higher rungs [36].

About half the global population uses coal or biomass for cooking and heating energy. There is a clear difference between rural and urban populations; 71% of the global rural population relies on biomass fuels, while 70% of urban residents use cleaner fuels such as gas or electricity [43]. There are substantial regional differences as well. In Africa, about 77% of households use coal or biomass and in Southeast Asia that figure is about 61%, compared to the world average of 41% [7]). In the past 30 years, the percentage of people relying on biomass cooking fuels has decreased, yet the absolute number of people has not significantly changed due to increased global population. Not all regions have had the same trends. In Africa, unlike the rest of the world, the absolute number of people using solid fuels has nearly doubled since 1980 [7].

Census data from India allows a glimpse the diversity in regional fuel choice. Wood is the dominant cooking fuel in 49% of households in India and a combination of crop residue and dung is the major fuel source in 18% of Indian households. In some states, though, dung and agricultural waste is the major fuel in over 55% of the households [14]. These values are only a record of the predominant fuel used for household cooking, and secondary fuels are not recorded [30]).

1.4.2 Stove technologies

Traditional cooking and heating stoves vary across the globe. In South Asia, stoves tend to be low to the ground, because cooks traditionally prepare and cook food at the floor level. South and Central American stoves tend to be standing-level and have a large flat surface for tortilla making. The three-stone fire is a traditional cooking stove still used in many places in rural Africa and across the world. Preferences for indoor or outdoor cooking vary across the world, as does the amount of kitchen ventilation. Globally, the majority of indoor biomass stoves do not vent outside the home (73%) [43].

There are two major reasons to improve stove design. The first is to reduce fuel consumption, and the second is to reduce indoor pollutant emissions. To improve fuel consumption, the designer improves the heat transfer efficiency from the combustion zone to the cooking pot. If the design objective is to reduce indoor air pollution, the combustion conditions can be changed to reduce pollutant formation or a chimney can be installed. Ideally, both of these objectives are met in stove design. However, an improvement in one design objective does not necessarily mean an improvement in other design objectives. For example, stoves designed to reduce the fuel consumption, can change the combustion conditions so that pollutant emission factors are increased compared to traditional stoves [39].

1.4.3 Health impacts of cooking and heating stove emissions

World Health Organization standards for indoor air concentrations of pollutants are often exceeded due to indoor cooking ($PM_{2.5}$: 10 mg/m^3, annual exposure [48] and CO: 7 mg/m^3, 24-hr exposure [49]). Exposure to combustion gases and particles can result in both acute and chronic human health effects. The most conclusive health impacts from biomass smoke are correlated with indoor particulate matter (PM) concentrations [4]; [24]. Exposure to other chemicals released from combustion of biomass or coal such as formaldehyde, nitrogen oxides, sulfur oxides, phenols, chlorinated acids, methyl chloride, dioxins, heavy metals, arsenic and fluoride chemicals also has known health effects. In addition, biomass combustion releases carcinogenic compounds such as benzene and polycyclic aromatic hydrocarbons (PAHs). Cooks who use biomass combustion stoves experience higher rates of cancer, cardiovascular and circulatory diseases, chronic respiratory diseases, and cataracts than populations using cleaner fuels [27]. Household air pollution due to cookstove smoke is the 4^{th} highest global burden of disease and is estimated to cause approximately 3.5 million deaths per year and over 100 million disability adjusted life years [27].

Figure 1.1 shows that exposure to $PM_{2.5}$ due to solid fuel cooking is a greater health risk than secondhand

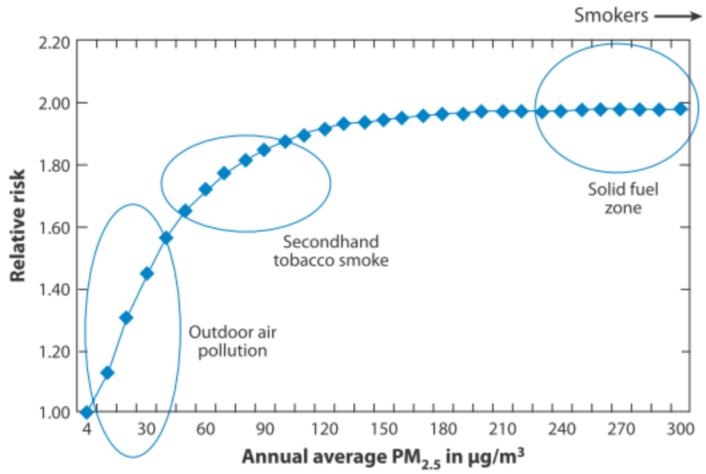

Figure 1.1: Relationship between $PM_{2.5}$ concentrations and relative risk of ischemic heart disease [37]
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smoking, but less than active smoking. Indoor air concentrations of $PM_{2.5}$ need to be substantially reduced to reduce the outcomes of exposure [37]. The relationship between exposure and health outcomes is not linear; a 50% reduction in concentration from 200 $\mu g/m^3$ to 100 $\mu g/m^3$ may only reduce the risk of heart disease by 5% [37].

Reducing emissions does not always result in improved health outcomes. In communities with many stoves emitting in close proximity, high outdoor pollutant concentration is a health risk. In these communities, household-level improvements such as chimneys or emission reductions may not result in significant health improvements [36]. Pollutant concentrations found in degraded outdoor air quality are usually lower than indoor concentrations and but cause similar kinds of health outcomes compared to indoor cooking [27].

1.5 Introduction to brick production technologies

The fired clay brick is the most common building material in India [34] and is widely used throughout South Asia [12]. Approximately 87% of the 1.5 trillion clay bricks produced annually are made in Asia and over 20% of those are produced in South Asia (India, Pakistan, Bangladesh and Nepal). These bricks are typically fired in small-scale traditional kilns that burn coal or biomass without pollution controls.

Emissions of particulate matter and gaseous pollutants affect the respiratory health of on-site workers [20], [54] and can degrade local air quality [15], [19]. Brick kilns clustered on the outskirts of population centers pollute air quality in cities such as Dhaka, [2] New Delhi, [16] or Kathmandu. In the Kathmandu valley, for example, brick kilns have been estimated to be responsible for about 28% of the PM_{10} concentration [42]. On a national scale, brick kilns are estimated to produce 7% of black carbon (BC) emissions in India [31] and China [47]. UNEP [44] and the U.S. EPA [46] recommend modernizing brick kilns as a promising measure to reduce short-lived climate forcers, such as BC, and slow near-term climate change. These recommendations were based on estimated emission factors [35].

To support and evaluate these recommendations, and to provide input to regional and global air quality models, direct measurements from the most relevant fuels and kiln types are necessary. In particular, there are no previous measurements of BC from brick kilns in South Asia. This study reports emissions and characteristics of thirteen kilns that include kiln types, fuels, and production scales representative of the major kiln types present in South Asia. The majority of South Asian bricks are produced in the Bulls Trench Kiln (BTK), and batch kilns are the second most common production method. Both BTKs and a batch kiln were measured in this study.

The second objective of this research is to study improved kilns that could be implemented as replacement options in South Asia. This study included four types of improved kilns; Two types of zig-zag kiln, which is an improved type of BTK, a Vertical Shaft Brick Kiln (VSBK), and a tunnel kiln.

1.6 Research objectives

1.6.1 Emissions from household biomass combustion

1. Calculate emission factors from prevalent stove and fuel combinations in the Tibet and Nepal.

These results can improve the accuracy of total emissions estimates from stoves in these regions. Results can also be used to estimate the amount of pollution emitted into households. Comparisons of stove and fuel combinations can help identify populations with the greatest health risks due to pollutant exposure.

1.6.2 Industry combustion emissions in rural Nepal

1. Conduct pilot emissions measurements of small-scale industry combustion in rural Nepal.

These results are a first estimate of emission factors from sectors that have been overlooked in total emission estimates. These results allow emissions from these small sectors to be more accurately represented in total emission estimates. It also allows preliminary comparisons and recommendations to be made between biomass fueled pottery kilns.

1.6.3 Emissions from brick production in South Asia

1. Determine emission factors for kilns prevalent in South Asia. (bulls trench kiln and downdraft kiln).
2. Determine emission factors for improved kilns (zig-zag kilns, vertical shaft brick kilns, and a tunnel kiln) and compare to typical South Asian kilns.
3. Estimate the climate forcing due to brick production emissions in South Asia.

Emissions factors from brick kiln emission measurements allow comparisons between different brick making technologies. Results can be used to recommend improved kiln replacements that reduce emissions. In addition, these results can be used to estimate the total sector emissions of health and climate impacting pollutants, which can be used in regional pollution modeling and climate studies.

Chapter 2

Methods

Emissions testing can be done using several methods. The method typically used in laboratory setting is the full capture method, where the entire plume is collected in a hood. In this method, the pollutant concentrations and total flow rate are measured, allowing total pollutant emissions to be calculated. Emission factors can also be determined using this method if the mass of fuel consumed is recorded. Stack testing uses the same method, but instead of a laboratory hood, all emissions are carried out through the stack. The concentrations in the stack, stack flow rate, and fuel consumption are measured. However, the total capture method is often impractical or impossible in the field. A laboratory hood cannot be practically taken to household kitchens, so an alternative method is used.

In the partial capture method, only part of the plume is drawn into the sampling equipment for measurement. The concentration of carbon measured is used to approximate the fuel carbon, and can be used to determine an emission factor of the pollutant. The method is detailed in Section 2.2.

Emission measurements from all sources in this study included real-time CO_2, CO, scattering, and absorption. Integrated samples of $PM_{2.5}$, OC, and EC were collected on filters and analyzed in the laboratory. Table 2.1 summarizes all of the parameters measured and the method used and is detailed in Section 2.1. CO and $PM_{2.5}$ are pollutants of interest for health and climate impacts. OC, EC, and the particle optical properties are used to determine the climate effects of particle emissions. CO_2 measurements are required to calculate emissions factors.

Table 2.1: Summary table of measured species and characteristics.

Quantity Measured	**Method**
Particulate matter ($PM_{2.5}$)	Gravimetric analysis
Organic carbon (OC)	Thermo-optical analysis on quartz fiber filters
Elemental carbon (EC)	Thermo-optical analysis on quartz fiber filters
Carbon monoxide (CO)	Real-time electrochemical
Carbon dioxide (CO_2)	Real-time infrared absorption
Particle scattering	Red light scattering sensor
Particle absorption	Filter transmittance (PSAP)

2.1 Sampling methods

For all measurements, CO and CO_2 concentrations were measured in real-time (1 Hz) using an electrochemical sensor (SS1128, Senko) and a non-dispersive infrared sensor (Telaire T6615, GE), respectively.

Particles were measured downstream of a 2.5 μm cut cyclone (URG 2000-30ED). $PM_{2.5}$ was collected on 47 mm Teflon fiber filters (1.0 m pore size, FluoroporeTM Membrane Filters, FALP04700, Millipore) and was measured gravimetrically using a microbalance (Cahn C-31, Thermo Electron Corp) in a temperature and humidity controlled environment (20-25 C and 45-50% RH). EC and OC were collected on 47 mm quartz fiber filters (TISSUQUARTZ 2500QAT-UP, Pall) and measured using thermal-optical analysis [29] with a Sunset Laboratory OC/EC analyzer. An additional quartz filter behind the Teflon filter collected only adsorbed gas-phase carbon and was subtracted from the primary quartz filter mass to correct for gas-phase adsorption [21]. Filters were sealed and kept in ice-packed insulated containers after collection. They were maintained at -4 C prior to analysis to prevent loss of volatile organic carbon [11].

Particle optical properties were measured in real-time (1 Hz). Particle scattering was measured with a single-angle red-wavelength light sensor (635 nm) designed by Aprovecho Research Laboratory. Absorption was measured using a 3-wavelength (467, 530, and 660 nm) Particle Soot Absorption Photometer (Radiance Research). Corrections were applied as in Chen (2012) [8].

Flows through each filter, used to calculate particle concentrations, were measured in real-time with mass flow meters (Honeywell AWM3300V) after each filter. In addition, the system flows were checked in-line at six sampling points in the system using a thin film flow calibrator (mini-BUCK calibrator APB-805000) before and after each measurement. The system was checked for leaks by applying negative pressure to the entire closed system in the lab, prior to each sampling trip, and by monitoring system flows in the field.

2.1.1 Sampling method for stoves and small industries

Most stove and small industry stoves did not have stacks and a partial sample was drawn from the smoke plume. Stove emissions were drawn from the plume at 10 cm to one meter above the cooking vessel using sampling area probes described in Roden et al. (2006) [32]. The height was determined by selecting a location as near to the stove as possible, while allowing the cook clear and free access to operate without influencing the cooking routine.

When a chimney was present, the sample was drawn from the chimney using a modified version of the Roden et. al. [32] probe. The small holes in the probe arms could clog with particles due to high concentration in some chimneys, so the probe arms were removed and a 3/8 in hole was opened perpendicular to the stack flow, in the center of the chimney.

2.1.2 Sampling method for brick production emissions

The sampling system described by Roden et al. (2006) [32] was used for measurements, but changes were made to accommodate stack sampling (Figure 2.1). A nephelometer was replaced with a portable light scattering sensor. A variable-size nozzle attached to stainless steel tubing withdrew sample from the stack and a bypass flow stream was added to achieve isokinetic sampling. Flue gases and particles were continuously drawn from the stack into sampling equipment. Filtered and desiccated ambient air was mixed with sample gas to dilute and cool the sample stream and lower the relative humidity before measurement.

The flue gas temperature, moisture content, total suspended particulate matter, and flow rate were

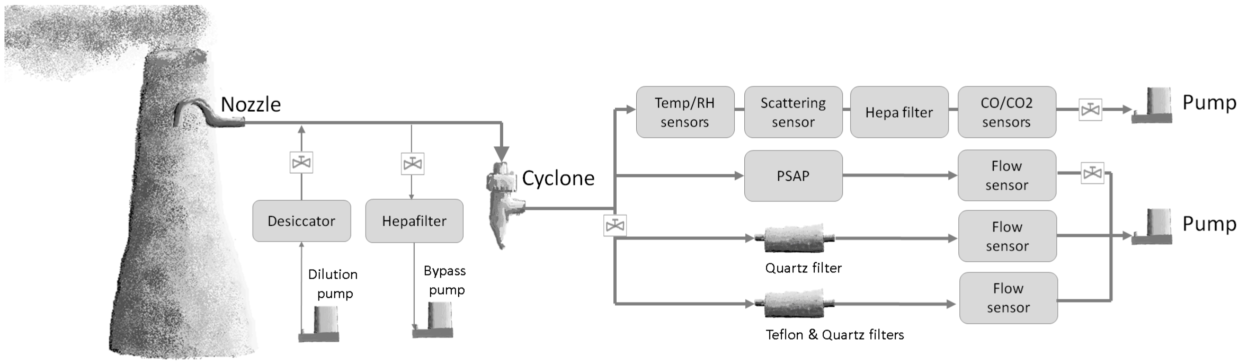


Figure 2.1: Schematic of stack sampling train.

determined in the stack and the methodology and results can be found in Athalye et al. (2013) [1]. Flow measurements were used to select nozzle sizes for isokinetic sampling and temperature was used to correct to standard conditions.

Platforms for measurement were built considering EPA sampling location guidelines (eight stack diameters downstream and two diameters upstream of any flow disturbance), but modifications were made when required for structural integrity and safety. At kilns with large stacks (BTK and zig-zag), samples were drawn from a porthole in each stack at 11-30 m from the ground. Samples from the downdraft and tunnel kilns were taken at 6 m and 9 m above ground level, respectively. VSBKs had smaller stacks and the sample was taken two meters above the top layer of bricks. The VSBK measured in India had two stacks and samples were taken from both stacks consecutively.

Measurements were taken during February - May in 2011, and 2012. Three tests ranging from 20 to 60 minutes were done at each kiln. The target test length was one hour, but was adjusted to achieve optimal filter loading.

2.2 Data analysis methods

2.2.1 Emission factors

Emission factors (g pollutant/kgfuel) were calculated using the carbon-balance method [32]; [52], which employs conservation of carbon mass before and after combustion. The measured carbon concentration is used to infer the mass of the fuel that yields one cubic meter of flue gas:

$$F = ((CO_2 + CO) * 12)/(C_{fuel} * V_m * 1000)$$

where CO and CO_2 are dry stack concentrations, in mole fraction, 12 (g/mol) is the molar mass of carbon, V_m is the molar volume and C_{fuel} is the carbon mass fraction of the fuel. The stack concentration of each pollutant (C in g/m^3) divided by F (kgfuel/m^3) yields the emission factor (EF_{fuel}) in g/kgfuel. The carbon balance method inherently assumes that other carbon-containing emissions are negligible compared with CO_2 and CO [38].

The carbon-balance method was also used to calculate emission factors of optical emission factors. Measurements of scattering or absorption (m^{-1} or m^2/m^3) were divided by F, resulting in EF_{fuel} in m^2/kgfuel.

Absorption emission factors were calculated in all three wavelengths. Scattering and absorption are approximately proportional to $PM_{2.5}$ and BC concentration, respectively, although the exact ratio is uncertain because of variable particle properties. These values indicate the relative magnitude of emission in real-time.

2.2.2 Combustion efficiency

Combustion efficiency is the ratio of carbon that is fully combusted, forming CO_2, to the carbon in the original fuel. A combustion efficiency value of 1 would indicated that all fuel carbon is fully combusted. An combustion efficiency approximation (CE) is used in this study. The fuel carbon is approximated using the carbon measured in CO_2 and CO and is shown in the following equation.

$$CE = \frac{CO_2}{CO_2 + CO}$$

CO_2 and CO are mixing ratios in ppm.

2.2.3 Particle properties

Single scattering albedo (SSA) is the ratio of scattering to extinction and is calculated using the following equation:

$$SSA = \frac{b_s}{b_s + b_a}$$

Where, b_s is particle scattering in Mm^{-1} and b_a is absorption in Mm^{-1} of particles in the red (660) wavelength. The Absorption Angstrom Exponent (AAE) is a measure of the wavelength dependence of particle absorption. The following formula was used to determine the AAE in this study.

$$AAE = \frac{-ln(b_{a_R}/b_{a_B})}{ln(660/467)}$$

b_{a_R} is particle absorption in Mm^{-1} in the red wavelength (660 nm), b_{a_B} in the absorption in the blue wavelength (467 nm).

2.2.4 Real-time data analysis

CO_2, CO, scattering, and absorption was recorded at 1 Hz. The data was broken down into one minute periods and averaged. CE, SSA, and AAE were calculated using the equations above for each period. These values are used to show how the emission characteristics vary within a measurement event or group of events.

2.2.5 Kiln specific data analysis

Emission factors are typically calculated by multiplying measured stack flow with pollutant concentrations and dividing by observed fuel consumption rate. Flow measurements had large uncertainties due to rapid velocity fluctuations and low flow velocities that were near the detection limit of the pitot tube. These measurements were found to be unreliable for emission factor calculations. When suitable measures of exhaust flow are available, flow-based measurements of emission factors are preferred. The carbon balance method was used as an alternative, providing emission measurements that would otherwise be unobtainable.

Two other normalized emission factors were used to compare brick kiln emissions. An energy based emission factor (EF_{energy}) in grams pollutant per MJ) was determined by dividing each EF_{fuel} by its lower heating value. A production-based emission factor ($EF_{kgbrick}$ in grams pollutant per kg fired brick) was calculated by multiplying EF_{fuel} by the fuel consumption rate (kg fuel per day) and dividing by the brick production rate (kg brick per day). The latter measure combines the effects of combustion cleanliness and production efficiency.

2.2.6 Radiative forcing

Radiative forcing from current emissions and mitigation scenarios was estimated using forcing-per-emission values [6] for measured CO_2, CO, SO_2 [1], and EC. Forcing-per-emission values for organic matter were used; measured OC was multiplied by 1.9 to approximate organic matter mass. EC was used as a proxy for BC. The uncertainty of this approximation is small compared to the uncertainty in the radiative effects of BC. Direct forcing, particle effects on clouds, and BC effects on snow albedo were included as in Bond et. al. (2013) [6]. NO_x and non-methane volatile organic carbon were not measured and were omitted from the calculation. Consistent with current emission-trading schemes, radiative forcing was integrated over 100 years after emission.

In order to calculated the radiative forcing of non-carbonaceous material, the mass was approximated as fly ash or mineral matter. To date, there have been no estimates of forcing by fly ash, and reports of forcing by suspended mineral matter usually encompass size ranges. As an approximation, the same forcing as organic matter was used. Fly ash has nearly the same refractive index to organic matter [50] and particles of the same size would thus scatter and absorb the same amount, so the direct forcing per mass would be similar. Mineral matter is hydrophobic and primary particles would require coating in order to interact with clouds, as is the case with primary organic matter.

Chapter 3

Emissions from stoves and small industries

Emission measurements were conducted in Nepal and Tibet where biomass fuels are commonly used for household cooking, heating, and small industries. Stoves and fuels were selected based on the most common practices in the study regions. Tests were conducted in villages and normal patterns of combustion were not changed; the typical household stove user operated the stove and obtained and chose the fuels. Similarly, fuels and fuel-feeding practices used in the small industry combustion was the choice of the operator. All of the stoves and industries measured are listed in Table 3.1.

3.1 Description of stoves and fuels measured

Emissions measurements from stoves and fuels were conducted in the Tibetan plateau and the Nepal Terai (Southern plains) region. There are some distinguishing differences between the stoves and fuels used in the two regions. Both chimney and non-chimney stoves are used in Tibet, whereas in the Nepal Terai only non-chimney stoves were identified and measured. Stoves in Tibet are used for both heating and cooking and are operated even when no food is being prepared. In Nepal, the stoves were primarily used for cooking; cooks discontinued fuel feeding when the meal was complete. However, the heat from the stove replaced other forms of household heating. The distinction between heating and cooking stove uses is not always clear. For the purpose of this study, all stoves are considered both heating and cooking stoves.

Both dung and wood are used as stove fuel in both regions. In Nepal, dung is typically mixed with rice husks or straw and is from cows or buffalo. In Tibet, yak dung is typically used. Wood types also differ between the two regions, but the species were not identified. The farming communities in Nepal produced corn, rice, and hay. The waste was used for cooking and heating in Nepal, but this practice was not found in Tibet.

3.1.1 Tibetan cooking and heating stoves

Three stove types were measured in the Tibetan plateau that were used for both cooking and heating. An open combustion chamber stove without a chimney was measured that was used in mobile tent houses. Two type of metal stoves that have a chimney were also measured in permanent wooden houses (Figure 3.1).

Table 3.1: Combustion devices and fuel combinations measured.

Data set	**Stove**	**Fuel**	**Type**	**Location**	**Tests**
	Traditional, open	Dung	Trad	Tibet	14
	Metal with chimney	Dung	Trad	Tibet	13
Tibetan stoves	Metal with chimney	Wood	Trad	Tibet	15
	Nepal traditional clay	Dung, Wood	Trad	Nepal	4
	Nepal traditional clay	Dung, Wood, Bamboo	Trad	Nepal	2
	Nepal traditional clay	Wood	Trad	Nepal	4
	Nepal traditional clay	Small Branches	Trad	Nepal	2
	Nepal traditional clay	Sugarcane, Wood	Trad	Nepal	1
	Nepal traditional clay	Sugarcane	Trad	Nepal	9
	Nepal traditional clay	Sugarcane, Small Branches	Trad	Nepal	2
	Nepal traditional clay	Sugarcane, Corn Leaves	Trad	Nepal	1
	Nepal traditional clay	Dung, Sugarcane	Trad	Nepal	2
Nepalese stoves	Nepal traditional clay	Dung	Trad	Nepal	2
	Straw Heating	Straw	Trad	Nepal	1
	Restaurant	Wood	Trad	Nepal	2
	Candy Making	Wood	Trad	Nepal	1
	Wood Kiln	Wood	Impr	Nepal	2
Nepalese industries	Straw Kiln	Straw	Trad	Nepal	4

Emission measurements from stoves that use yak dung fuel were taken in the Nam Co region of the Tibetan Plateau, at an elevation of 4730 m above sea level. Yak dung is the only fuel available in the high elevations where woody plants can no longer survive. Wood stoves were sampled in the lower elevation regions of the Tibetan Plateau.

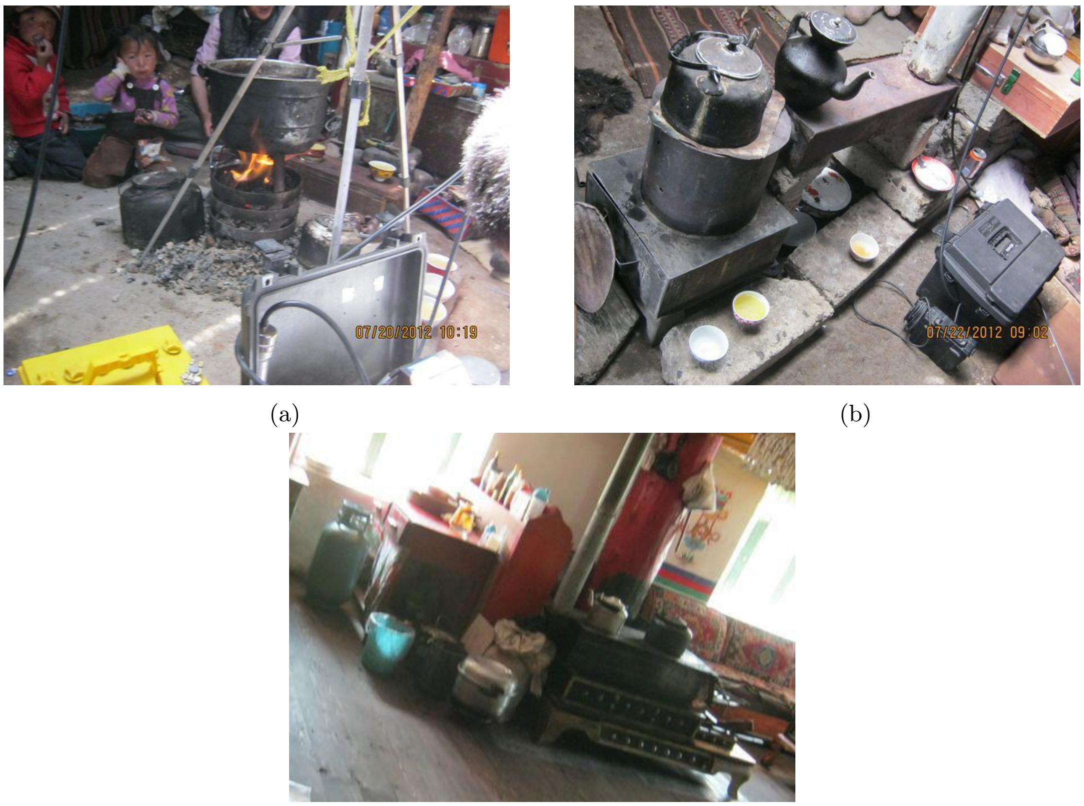
3.1.2 Nepal cooking and heating

Household stoves in the Nepal Terai region were homemade, permanent clay structures that were built into the floor of the kitchen (Figure 3.2a). Most had two fueling ports on the side of the stove. Each fuel feeding port had either one or two ”burners”, or pot spaces on the top of the stove. In the double burners, one burner is the hotter, primary cooker, and the other was to pre-warm a dish, or to keep food warm after cooking. Long wood and agricultural waste fuel would be slowly fed into the side ports. Dung in this region was usually mixed with rice husks and packed around a stick, so the long pieces could be easily fed into the stove.

In the winter months, it was common practice in the Nepal Terai region to burn piles of straw for heating both indoors and out (Figure 3.2b). One pilot emission test of outdoor straw heating was conducted. The straw was stored in uncovered heaps in the village, and was usually damp when burned. The smoke from heating in the village would be high enough to significantly reduce visibility, especially in the early morning.

3.1.3 Nepal small industry

A pilot study of previously unmeasured village enterprise sources was conducted in Nepal. Small industries that use biomass fuels were identified by in-country partners in Nepal. A restaurant, two pottery kilns, and a candy making industry were sampled (Figure 3.3). Only one to two days of testing were conducted at each



(a) (b)

(c)

Figure 3.1: Traditional stoves measured in Tibet. (a) Yak dung stove without a chimney used in a tent house in Tibet. (b) Yak dung stove with a chimney used a permanent house in Tibet. (c) Wood stove with a chimney used in a permanent house in Tibet.

(a) (b)

Figure 3.2: Household combustion sources in Nepal Terai. (a) Typical clay stove used in Nepal. These stoves use many types of available fuels, including solid wood, local shrubs, agricultural waste, and dung. (b) Smoldering straw used for heating.

site.

A traditional kiln that used straw fuel was measured (Figure 3.3b). Here, pottery pieces and straw were set in a pile on the ground and covered with a layer of ash. The only permanent structure of the kiln was a single stone wall that was on one side of the kiln. The firing took place over several days. The second kiln measured was a wood fired kiln in an enclosed box with a chimney (Figure 3.3c). Firing lasted from early morning until late in the evening of a single day.

A local candy making operation was also monitored (Figure 3.3a). Stoves were used continuously over the day to heat pots of fruit for candy making. The stove operation was the same as home stoves in Nepal, but here there was one large side port for fuel feeling for each large burner.

Restaurant-scale stoves were larger versions of home stoves. The one measured exclusively used wood fuel and was operated continuously from early morning until evening.

3.2 Results and discussion

3.2.1 Tibetan stoves

Emission factors (EF) for CO, $PM_{2.5}$, OC, EC, and optical cross-sections (m^2/kg fuel) for scattering and absorption are shown in Table 3.2 for three stove/fuel combinations measured in Tibet. Open yak dung stoves produced higher emission factors compared to chimney stoves. CO EF was greater in the open stove than either chimney stove and significantly greater than the wood chimney stove ($p < 0.01$). $PM_{2.5}$ was significantly greater than both the dung and wood chimney stoves ($p = 0.04$ and $p < 0.01$, respectively). Both OC and EC emission factors from the open stove were greater than in the wood chimney stove ($p < 0.01$).

(a) (b)

(c)

Figure 3.3: Small industry combustion in Nepal. (a) Candy making. Fruit is boiled for several hours in large pots using wood fuel. (b) Straw fuel pottery kiln in Nepal. (c) Improved pottery kiln using wood fuel and an enclosed combustion chamber.

The differences in EFs between the chimney stoves using dung and wood, suggests that the fuel choice influences the emissions. The chimney stoves that were operated with wood had lower emission factors than the dung stove for most pollutants. $PM_{2.5}$ emission factors were about 3 times lower and CO emissions factors were 35% lower in wood stoves. The difference is statistically significantly for both $PM_{2.5}$ and CO ($p < 0.01$).

The scattering sensor over-ranged in half of the tests in Tibet and in all three of the stove/fuel combinations. The scattering results (including the SSA) were omitted from the averages when over-ranging occurred. The scattering emission factor only represents a subset of the dataset and is highly uncertain.

Emission factors in Tibet are higher than those measured in other parts of the world. For example traditional stoves measured in Honduras had a $PM_{2.5}$ emission factor of 8.2 g/kg fuel and improved chimney stoves emitted 4.5 g/kg. CO emission factors in Honduras were 118 g/kg from traditional stoves and 76 g/kg from chimney stoves [33]. Even the lowest emitting, wood chimney stove in Tibet had higher emission factors than in Honduras.

The reason for regional differences in emission factors may be due a combination of stove design, regional fuel variability, or atmospheric conditions. For example, the combustion characteristics of open flames is known to be affected by atmospheric pressure. Lower and slower burning rates have been observed in high altitude combustion [26]. There is thus, the potential that the high observed CO and $PM_{2.5}$ are influenced by atmospheric pressure. The atmospheric pressure in Tibet, at the dung stove measurements, was 567 hPa, and for the wood stoves was 687 hPa. In comparison, stoves measured in Nepal were measured at 989 hPa and in Honduras, around 1000 hPa.

Table 3.2: Emission factors for three stove and fuel combinations measured in Tibet. The units are in g/kg fuel for CO, $PM_{2.5}$, OC, and EC, and in m^2/kg fuel for scattering and absorption. Absorption is shown here in the green wavelength (530 nm). The range represents both the measurement uncertainty and the variability of the measurements.

	CO EF	**$PM_{2.5}$ EF**	**OC EF**	**EC EF**	**Scat EF**	**AbsG EF**
Open, Dung	281.3 ± 249.2	59.5 ± 55.8	39.8 ± 38.8	4.3 ± 7.0	312.7 ± 355.6	21.8 ± 17.7
Chimney, Dung	236.0 ± 87.2	33.8 ± 18.6	22.8 ± 14.7	3.7 ± 7.5	111.6 ± 166.3	14.8 ± 7.8
Chimney, Wood	151.6 ± 49.3	12.4 ± 10.7	9.9 ± 15.4	0.9 ± 1.3	65.1 ± 74.6	15.4 ± 12.4

In Figure 3.4, one minute averages of real-time data are used to produce frequency distribution plots of combustion efficiency (CE), single scattering albedo (SSA), and the absorption angstrom exponent (AAE) between blue and red wavelengths. The CE in the open dung stove was lower than in the chimney stoves, and particles produced tended to be scattering, suggesting that there is less oxygen available in this stove and that the combustion is mostly smoldering instead of flaming. The AAE tended to be higher in the open stove than in the chimney stoves and varied from less than 1 to 8. Very little black carbon was produced in any part of the typical combustion process in the open stoves.

Chimney stove that were operated with wood fuel had the highest CE with the least variability. They tended to produce more black carbon, and a greater range of scattering to absorption ratios over the combustion. The AAE indicates that the particle mixture was more absorbing over a range of wavelengths compared to the dung stoves. The chimney stoves produced a mix of organic and black carbon throughout the combustion events.

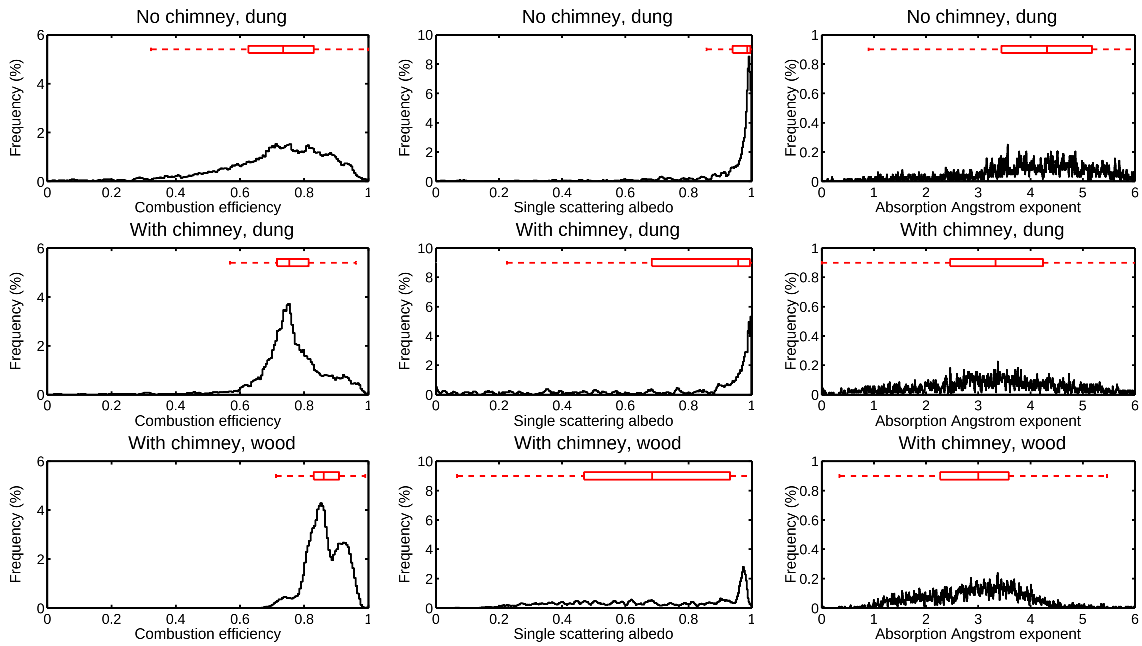


Figure 3.4: Frequency plots of CE, SSA, and AAE for traditional Tibetan stoves using one minute averages of real-time data.

3.2.2 Nepalese household cooking and heating

In Nepal, a clay stove was used with a variety of fuels and fuel mixtures, allowing an indication of the effect of fuel choice on emission characteristics (Table 3.3). In most measured cooking events, a mixture of fuels was used, sometimes in series but often multiple fuels were used concurrently. The highest CO emission factors were measured from stoves using sugarcane mixed with cow dung and the lowest were from sugarcane mixed with wood. Yet, CO emission factors for pure dung were lower than pure wood. Because of the diversity of fuels, there are not enough tests to determine statistical significance between fuel combinations. The average CO emission factor from traditional stoves in Nepal is 103 $\pm$ 29 gCO/kg fuel.

The $PM_{2.5}$ emission factor was highest in the sugarcane and small branches mixture and lowest in the case where pure wood fuel was used. Cooking events that contained wood had lower $PM_{2.5}$ emission factors that tests containing dung or sugarcane.

Elemental carbon emission factors were highest in events that used sugarcane fuels and lower in events that used dung fuel. The ratio of EC to total carbon was 0.5 $\pm$ 0.3 for sugarcane containing events and 0.3 $\pm$ 0.2 for both dung and wood tests. Absorption emission factors had the clearest correlation with fuel type; sugarcane fuels produced more absorbing particles than emissions from either wood or dung. In tests where sugarcane waste was mixed with other fuels, less BC was produced that in the case of pure sugarcane fuel.

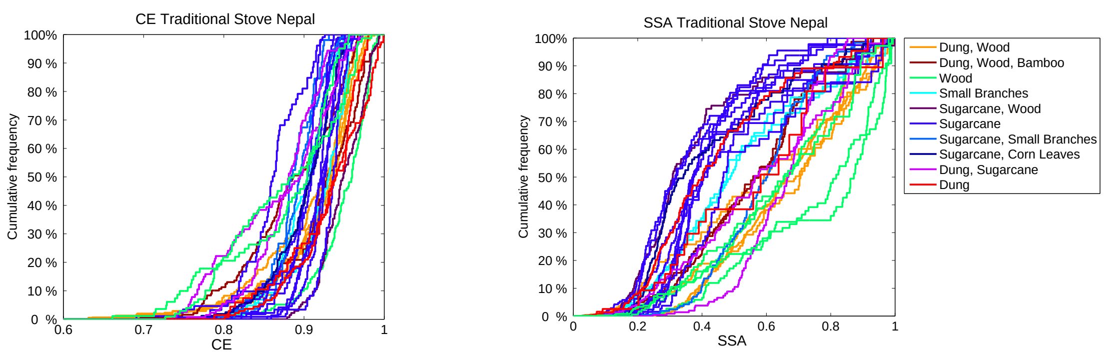
Heating with straw produced higher emission factors of CO and particles compared to cooking stoves in Nepal. CO EF in straw heating was nearly double the value for stoves, and $PM_{2.5}$ EF was over 5 times greater. The combustion in straw heating was predominately scattering; the SSA was 0.96 and EC/TC was 0.6.

Figure 3.5 shows the cumulative frequency curves of CE and SSA for all stove events. Two tests with pure wood had a higher frequency of low CE events than most of the sugarcane containing tests. The SSA curves show that the pure wood tests tended to have a higher frequency of high scattering events, while the

Table 3.3: Emission factors for various fuel combinations used in Nepal. The units are in g/kg fuel for CO, $PM_{2.5}$, OC, and EC, and in m^2/kg fuel for scattering and absorption. Absorption is shown here in the green wavelength (530 nm). The straw combustion for heating was not in a stove. The uncertainty includes measurement uncertainty and variability between tests. Those measurements with no uncertainty shown had only a single test. The rows labeled all test with dung, wood, or sugarcane summarize all tests in which that fuel type was present.

Fuel	**CO EF**	**$PM_{2.5}$ EF**	**OC EF**	**EC EF**	**Scat EF**	**AbsG EF**
Dung, Wood	92.1 ± 11.4	8.4 ± 6.3	3.4 ± 3.1	1.2 ± 0.9	16.1 ± 7.2	15.0 ± 4.0
Dung, Wood, Bamboo	99.7 ± 44.9	5.8 ± 1.3	0.5 ± 3.0	0.8 ± 1.1	7.5 ± 1.4	15.6 ± 5.4
Wood	102.6 ± 42.0	4.2 ± 1.4	2.4 ± 0.9	1.0 ± 0.6	12.3 ± 12.1	10.9 ± 5.7
Small Branches	103.6 ± 18.5	7.7 ± 2.9	3.6 ± 1.9	1.2 ± 0.6	14.7 ± 9.3	18.2 ± 7.7
Sugarcane, Wood	53.8	4.3	1.5	1.5	7.5	18.4
Sugarcane	103.1 ± 28.1	6.7 ± 2.4	1.9 ± 1.2	2.3 ± 1.0	12.2 ± 5.2	25.1 ± 5.6
Sugarcane, Small Branches	131.8 ± 18.3	9.9 ± 3.0	4.6 ± 4.1	1.4 ± 0.3	18.3 ± 7.1	20.7
Sugarcane, Corn Leaves	107.4	5.4	1.7	2.6	7.7	21.6
Dung, Sugarcane	141.6 ± 12.6	8.2 ± 2.8	3.6 ± 3.8	0.5 ± 0.1	8.7 ± 2.7	7.5 ± 1.9
Dung	76.4 ± 10.1	6.1 ± 3.6	–	–	6.0 ± 4.4	12.4 ± 10.3
All tests with dung	100.4 ± 29.3	7.4 ± 4.0	2.7 ± 3.0	0.91 ± 0.77	10.9 ± 6.5	13.1 ± 5.6
All tests with wood	97.3 ± 30.1	6.4 ± 4.0	2.4 ± 2.5	1.05 ± 0.77	12.8 ± 8.5	13.5 ± 5.0
All tests with sugarcane	109.1 ± 31.3	7.1 ± 2.6	2.5 ± 2.1	1.83 ± 1.01	11.9 ± 5.4	21.5 ± 7.8
All Stoves	**102.5 ± 29.1**	**6.9 ± 3.0**	**2.6 ± 2.2**	**1.50 ± 0.96**	**12.0 ± 6.8**	**17.8 ± 7.8**
Straw Heating	198.5	39.0	30.1	1.9	185.3	11.3

sugarcane containing tests had a higher frequency of absorbing events. The sugarcane, corn husks, and dry leaves all tended to combust in rapid flaming events that have high combustion efficiency and black carbon emissions.



(a) Combustion efficiency

(b) Single scattering albedo

Figure 3.5: Cumulative frequency of CE and SSA for various fuel mixtures used in traditional Nepali stoves. Each event was broken down into one minute periods. Each line represents a single test. The colors represent the fuel mixture used in the cooking event.

3.2.3 Small industry pilot study in Nepal

Emissions factors from small industries in Nepal are shown in Table 3.4. The CO emission factors in the industries that used wood were within the variability observed in cooking stoves in Nepal. The CO EF from the restaurant was lower than most other stoves and industries. The candy making and restaurant stoves used wood fuel and were operated the same as household stoves in Nepal. The CE, SSA, and AAE frequency plots (Figure 3.6) are similar to household stoves, suggesting that operation and stove design play a determining role in the emissions produced in these industries.

Pottery kilns had very different operations than stoves and the emission factors and frequency trends differed from household stoves in Nepal. Emission factors in the pottery kiln tended to have high variability because the combustion changed throughout the firing process. In the wood pottery kiln, there was a slow increase in the heat over several hours, followed by a cool-down phase. The measurements captured the majority of the firing process; about half an hour was missed halfway into the event for a filter change. Four tests were conducted over two days at the straw kiln, capturing the majority of the event. The straw pottery kiln had a higher $PM_{2.5}$ EF and CO EF than the wood kiln and higher CO EF compared to stoves in Nepal.

The emissions from the wood pottery kiln had a high ratio of black carbon; SSA was 0.3, EC/TC ratio was 0.8. In comparison, the straw pottery kiln emitted negligible black carbon; it had an SSA of 0.96 and an EC/TC ratio of 0.01. The EC was 78% of the $PM_{2.5}$ mass in the wood kiln and 22% in the average household stove in Nepal. The wood kiln is considered to be an improved pottery kiln.

Table 3.4: Emission factors from small industry combustion in Nepal. The units are in g/kg fuel for CO, $PM_{2.5}$, OC, and EC, and in m^2/kg fuel for scattering and absorption. Absorption is shown here in the green wavelength (530 nm). One to four tests were conducted at each site.

Industry and fuel	**CO EF**	**$PM_{2.5}$ EF**	**OC EF**	**EC EF**	**Scat EF**	**AbsG EF**
Restaurant (Wood)	54.2	7.2 ± 0.8	2.9 ± 0.5	3.6 ± 1.1	12.2 ± 2.3	32.5 ± 6.0
Candy Making (Wood)	129.9	4.1	2.4	0.4	4.1	9.6
Pottery Kiln (Wood)	101.2 ± 99.2	1.9 ± 1.2	0.3 ± 0.3	1.5 ± 0.8	4.9 ± 2.8	15.3 ± 7.0
Pottery Kiln (Straw)	246.5 ± 104.2	6.7 ± 5.4	2.6 ± 7.3	0.02 ± 0.04	22.3 ± 17.9	0.9 ± 0.7

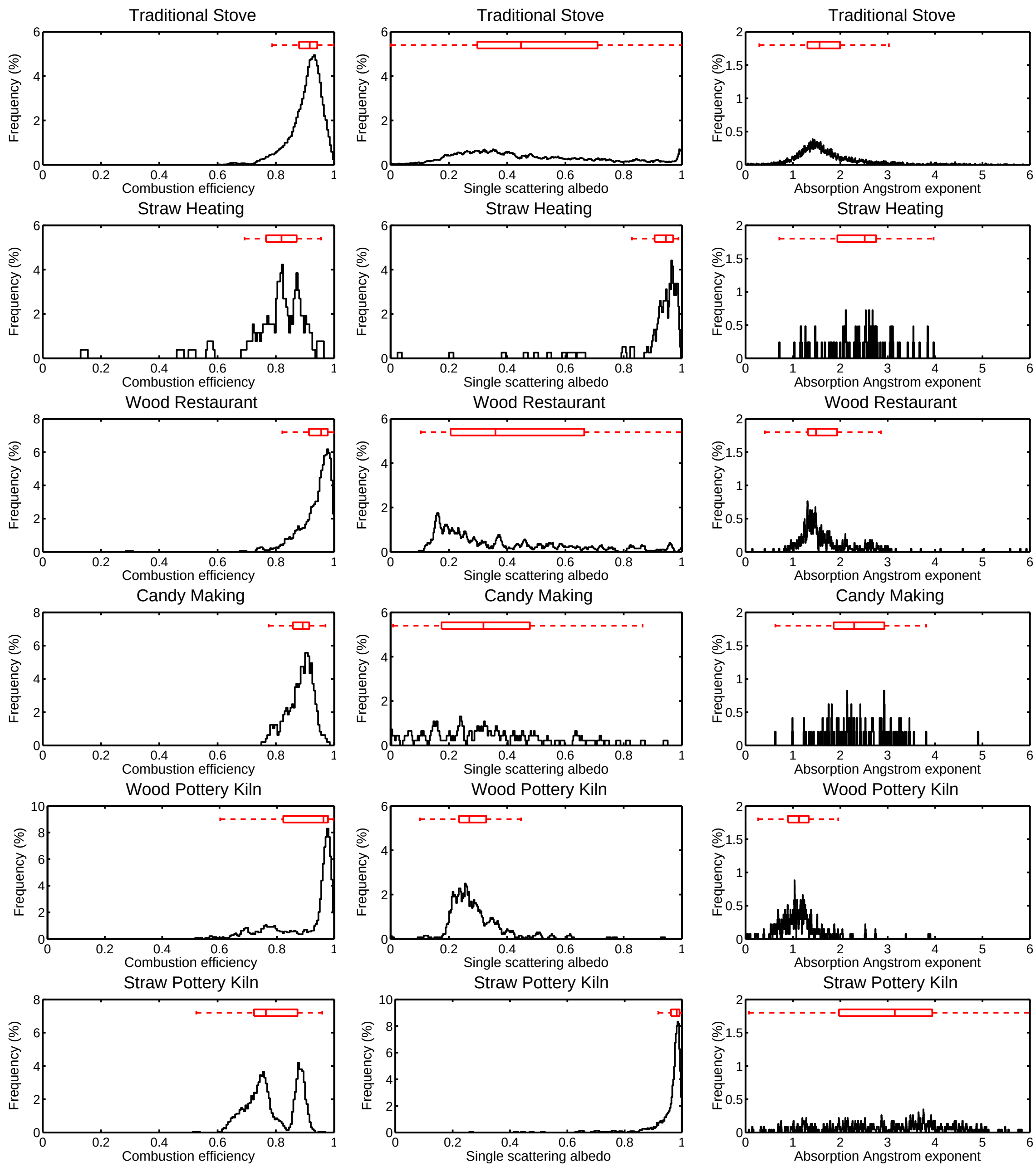


Figure 3.6: Frequency of 1 min averages of various emission sources in Nepal.

Chapter 4

Emissions from brick production

4.1 Introduction to kilns and fuels

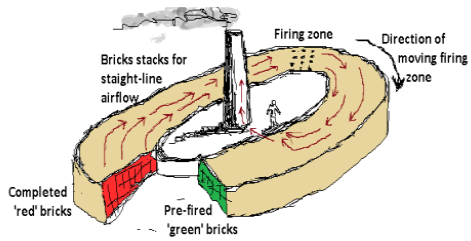
The universally recognized red clay brick is a 6000 year old building material produced from natural clay that is shaped, dried, fired, and cooled. Brick making is a fundamentally simple process, yet scaled production is accomplished using distinctly different techniques. Kiln diagrams and operational characteristics can be found in Figure 4.1.

Traditional brick kilns use a batch production method and are used for 25% of bricks produced in India [18]. A later improvement was continuous production, accomplished either by moving the firing zone through stationary bricks or by moving bricks through a stationary firing zone [18]. Continuous kilns are more energy-efficient than batch method kilns because the warm air released from the combustion zone is used to dry green (unfired) bricks and the newly fired bricks preheat the air before it reaches the firing zone [18]. This study included one improved batch kiln called a downdraft kiln and five types of continuous kilns (Bulls Trench Kiln (BTK), Vertical Shaft Brick Kiln (VSBK), two types of zig-zag kiln, and a tunnel kiln).

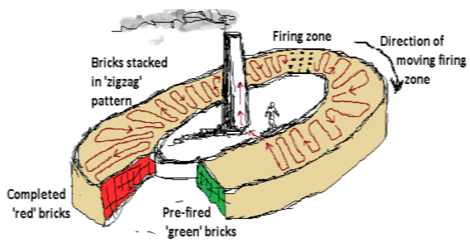
The BTK is the most common brick kiln in India and produces approximately 70% of the bricks in the country [28]. The BTK has a loop of stacked bricks with ducts that draft to a central stationary chimney. The firing zone shifts around the loop while green bricks are added and fired bricks are removed. The zig-zag kiln is similar in structure to the BTK, but the brick stacking is designed to retain the heated air longer. It is less prevalent than the BTK and accounts for 2-3% of the bricks produced in India [28]. Two types of zig-zag kiln were measured. The Natural Draft Zig-zag (NDZ) relies on buoyancy to induce stack flow while the Forced Draft Zig-zag (FDZ) uses a fan to generate flow.

In the VSBK, bricks are stacked vertically and the firing zone remains stationary in the center of the column. This kiln accounts for 1-2% of brick production in India and is more common in Vietnam and China [28].

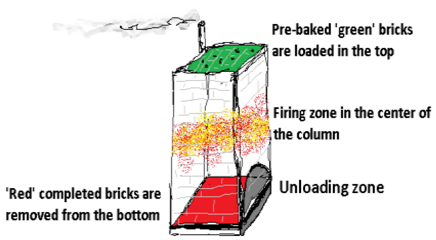
Tunnel kilns are the dominant kiln used where brick production is highly mechanized, such as in Europe and the United States. In this kiln, the firing zone is stationary, but the bricks are drawn horizontally using carts on rails. Few bricks in Asia are produced in tunnel kilns, but the numbers are growing, especially in Vietnam [18] and China. India has very few tunnel kilns in operation [28].



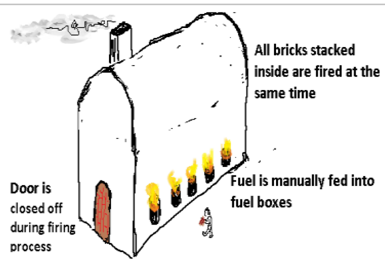
Bulls Trench Kiln (BTK): Bricks are stacked in an oval surrounding a central chimney. The air flows from the completed bricks, through the firing zone and up the central stack. The firing zone is slowly shifted around the kiln, towards the green bricks (clock-wise in the adjacent diagram). Green bricks are continuously added while red bricks are continuously removed.



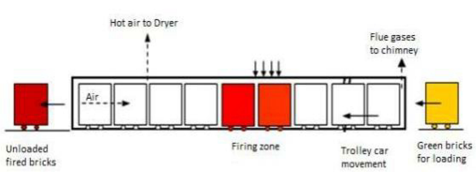
Zig-zag Kiln: The operations in this kiln are similar to the BTK. Air flows from the completed bricks, around the kiln and up the stack. In this case, the bricks are stacked such that the air takes a zig-zaging path through the kiln, thus retaining more energy to pre-heat and dry green bricks.



Vertical Shaft Brick Kiln (VSBK): In this continuous kiln, completed bricks are removed from the bottom of the column, the entire stack is shifted down, and new bricks are added to the top. The firing zone remains stationary in the center of the stack.



Downdraft kiln: This kiln has a permanent dome structure that reduces convective and radiative heat losses and central chimney that controls air flow better than a traditional intermittent kiln (*Maithel, 2012)*. Fuel is added through fireboxes, then the fireboxes are closed and the bricks inside are left to continue firing and cool. Air flows up to the top of the dome, down through the bricks and up through the chimney.



Tunnel kiln: Bricks in this kiln are drawn through a stationary firing zone on carts. External fuel is added to the firing zone from above. The air flows from the unloading zone, through the firing zone and up through a chimney.

Figure 4.1: Measured brick kiln types and operation characteristics [28].

4.1.1 Kiln selection

Kiln types were chosen for sampling either because they are common in South Asia (BTK and downdraft kiln) or could be implemented as improved kiln technologies (zig-zag, VSBK, and tunnel kilns). One VSBK and the tunnel kiln were measured in Vietnam, where brick production has rapidly transitioned from manually fired kilns to small tunnel kilns and mechanized VSBKs due to a government decree (No.115/2001/ND-CP, Hanoi, August 01, 2001). Random sampling was not possible because kiln selection relied on willing owners.

4.1.2 Fuel choice

Fuel feeding was monitored over approximately 24 hours during the emission testing period and fuel samples were collected for proximate and ultimate analyses. The higher heating value (HHV) was determined using ASTM D5865-99a.

Table 4.1: Kilns measured including size and fuels used during measurement period.

Kiln	**Place**	**Size**[1]	Fuel[2]
BTK 1	Garh Mukteshwar (U.P)	Large	66% Coal (25), 28% Wood (8), 6% Rubber (36)
BTK 2	Ludhiana (Punjab)	Large	100% Coal (32)
BTK 3	Arah (Bihar)	Medium	50% Steam coal (25), 50% Coal slurry (20)
NDZ 1	Varanasi (U.P)	Large	79% Coal (24), 21% Sawdust (18)
NDZ 2	Varanasi (U.P)	Large	65% Coal (18), 15% Petcoke (33), 20% Sawdust (18)
NDZ 3	Varanasi (U.P)	Large	53% Coal (19), 47% Mixed coal and sawdust (22)
FDZ 1	Varanasi (U.P)	Large	100% Coal (26)
FDZ 2	Howrah (W.B)	Large	100% Coal (20)
FDZ 3	Howrah (W.B)	Large	100% Coal (18)
VSBK I	Arah (Bihar)	Small	53% Steam coal3 (25), 47% Coal slurry (20)
VSBK V	Hungyen (Vietnam)	Medium	90% Coal ash[3] (6), 10% Coal powder (16)
DDK	Malur (Karnataka)	Small	100% Wood (17)
TK	Nam-dinh (Vietnam)	Large	90% Coal ash[3] (9), 10% Coal slurry (19)

[1] Kiln size references the Indian Central Pollution Control Board standards. Small: <15,000 bricks/day, Medium: 15,000-30,000, Large: >30,000 bricks/day.
[2] Percent of each fuel type by mass. HHV in megajoules per kg of fuel is in parenthesis.
[3] Internal fuels; fuel was mixed with brick clay before firing.

Kiln owners selected fuels used for normal operation (Table 4.1). Coal was the primary fuel in all kilns except the downdraft kiln. NDZ kilns used sawdust as a secondary fuel. In BTK1 rubber tire pieces were an additional fuel. Multiple fuels, when present, were added separately as determined by the operators. Coal mixed with pre-molded brick clay is referred to as internal fuel and was used in both VSBKs and the tunnel kiln. A summary of kiln fuel and energy efficiency can be found in Tables 4.2 and 4.3.

4.1.3 Operations and fuel feeding practices

In all kilns, fuel feeding was manual and discontinuous. BTKs and zig-zag kilns had the most distinct feeding and non-feeding periods, while VSBKs and tunnels were nearly continuous. Each test covered both fuel feeding and non-feeding periods.

Table 4.2: Elemental composition of the fuel.

KILN	**C**	**H**	**S**	**O**	**N**	**H_2O**
BTK 1	60	5.3	1.9	19.1	0.6	2.6
BTK 2	73	5.5	3.8	6.1	1	0.4
BTK 3	54	3.7	0.9	6.6	1.2	0.3
NDZ 1	54	4.7	1.3	16.3	1	6.4
NDZ 2	54	3.2	0.8	15.7	0	1.9
NDZ 3	58	3.2	1.5	7.9	0	2.2
FDZ 1	58	4.5	2.5	12.7	0.9	3.2
FDZ 2	54	3.4	0.6	5.6	0	7.4
FDZ 3	51	3.7	0.3	1.3	0	10.5
VSBK I	55	3.8	0.9	6.6	1.4	0.3
VSBK V	23	0.4	0.1	0.8	0.5	1
DDK	47	6.4	0.2	42.5	0.8	9.9
TK	31	0.6	0.1	3.1	0.2	2

The values are the percentage by weight of elements in the fuel used at each kiln. Other minerals are also present in the fuel.

Table 4.3: Kiln energy and fuel efficiency.

KILN	**Lower Heating Value** MJ/kg fuel	**Specific Energy** MJ/kg brick	**Fuel efficiency** kg brick/kg fuel
BTK 1	19.6	1.46	13.44
BTK 2	29.2	1.12	25.96
BTK 3	22.6	1.1	20.48
NDZ 1	20.5	1.21	16.89
NDZ 2	19.9	1.02	19.53
NDZ 3	20.4	1.02	20.13
FDZ 1	23.9	1.03	23.24
FDZ 2	19.7	1.11	17.8
FDZ 3	18.4	0.95	19.44
VSBK I	22.7	0.94	24.12
VSBK V	7.4	0.54	13.67
DDK	17.3	2.91	5.95
TK	9.7	1.47	6.59

In BTK and zig-zag kilns, fuel feeding was done manually by skilled operators until the visual characteristics of the flame indicated an adequate temperature, then feeding was stopped until the operator observed that more fuel was necessary (non-feeding period). Each test covered both fuel feeding and non-feeding periods. Fuel was added to the combustion zone in the BTKs in approximately 20 minute intervals. In the NDZ kilns, fuel feeding intervals were shorter and volumes were smaller than the BTK, resulting in more continuous fuel-feeding. The BTK and zig-zag kilns have seasonal operational in India due to monsoons. When the firing zone shifts through first loop around the kiln in the season, accumulated moisture from non-operational periods is released from the kiln. Each loop around the kiln is called a cycle. Measurements in this study were taken during first, mid-cycle, or final cycle.

In the intermittent downdraft kiln, fuel was added through fireboxes into the kiln for several hours. Then the fireboxes were closed and the kiln underwent a period of unattended brick firing Measurements were conducted during both stages.

The VSBK in India had simultaneous fuel feeding and brick loading. Coal was added in the gaps between layers of stacked bricks. In the Vietnamese VSBK, supplemental fuel was added to the combustion chamber via feeding chambers. Batches of bricks were loaded every 2-3 hours in both VSBKs. In India, brick batches consisted of six layers without precise control of spacing. In Vietnam, brick loading was more strict; batches were four layers, each with a specified internal fuel and brick packing density.

In the tunnel kiln, most of the fuel was internal, except for 10% which was added approximately every 30 minutes through holes above the firing zone when monitored temperature indicated the need.

4.2 Results and discussion

Emission factors for CO, $PM_{2.5}$, EC, and the ratios SSA and EC/TC are presented in Table 4.4. CO_2 and optical results are in Tables 4.5-4.7. For the kilns currently producing most of the regions bricks, EC/TC ratios are high, similar to those of diesel engines [13]. However, SSA values are much higher than those of pure BC, indicating that other non-carbonaceous material contributes to scattering. The following sub-sections discuss comparisons between kiln types.

4.2.1 Downdraft kiln

The downdraft kiln had mid-range emissions in terms of EF_{fuel}. However, because it required almost three times more energy to produce a brick (Table 4.3), its $EF_{kgbrick}$ is greatest for both CO and $PM_{2.5}$. The batch firing process and biomass fuel use in the downdraft kiln may cause the relatively low EC/TC ratio. A similar wood-burning batch kiln measured in Mexico produced emission factors in the same range [9]. The start-up and cool down phases likely have different emission characteristics, but were not included in this measurement. A true average emission factor would require monitoring the entire duration of the process.

4.2.2 BTK and zig-zag kilns

BTK and zig-zag kilns are discussed together because they have similar structures, allowing the possibility of conversion. The BTKs were the highest EC emitters of all kilns in EF_{fuel} and EF_{energy}. Compared to the BTK, zig-zag kilns had lower emission factors of CO ($p < 0.0002$), EC ($p < 0.02$), and absorption ($p < 0.02$). Low flow rates and arduous flow paths in the zig-zag kiln may decrease particle releases and allow more CO

Table 4.4: Average emission factors in EF_{fuel}, and $EF_{kgbrick}$ and standard deviation of test averages for all measured kilns.

Kiln	**CO**		**$PM_{2.5}$**		**EC**		**SSA**	**EC/TC**
	EF_{fuel}	$EF_{kgbrick}$	EF_{fuel}	$EF_{kgbrick}$	EF_{fuel}	$EF_{kgbrick}$		
BTK 1	36.5 ± 2.3	2.7 ± 0.2	4.4 ± 0.5	0.33 ± 0.04	3.7 ± 1.0	0.27 ± 0.07	0.73 ± 0.31	0.91 ± 0.35
BTK 2	53.8 ± 5.2	2.1 ± 0.2	3.7 ± 2.1	0.14 ± 0.08	2.7 ± 1.3	0.11 ± 0.05	0.68 ± 0.30	0.96 ± 0.46
BTK 3	26.4 ± 1.8	1.3 ± 0.1	1.7 ± 2.4	0.08 ± 0.12	1.8 ± 0.6	0.09 ± 0.03	0.76 ± 0.30	0.93 ± 0.42
NDZ 1	15.0 ± 1.0	0.9 ± 0.1	2.7 ± 1.1	0.16 ± 0.07	0.4 ± 0.4	0.03 ± 0.02	0.95 ± 0.38	0.66 ± 0.52
NDZ 2	6.9 ± 1.3	0.4 ± 0.1	0.5 ± 0.2	0.03 ± 0.01	0.2 ± 0.2	0.01 ± 0.01	–	1.00 ± 0.21
NDZ 3	10.7 ± 2.0	0.5 ± 0.1	3.8 ± 0.7	0.19 ± 0.03	0.2 ± 0.03	0.01 ± 0.002	–	0.85 ± 0.22
FDZ 1	19.7 ± 4.8	0.8 ± 0.2	1.2 ± 0.6	0.05 ± 0.02	0.5 ± 0.2	0.02 ± 0.01	0.62 ± 0.25	0.75 ± 0.38
FDZ 2	32.5 ± 4.7	1.8 ± 0.3	1.0 ± 0.2	0.06 ± 0.01	0.1 ± 0.05	0.01 ± 0.003	0.85 ± 0.34	0.76 ± 0.30
FDZ 3	21.7 ± 1.7	1.1 ± 0.1	0.6 ± 0.3	0.03 ± 0.02	0.07 ± 0.07	0.004 ± 0.004	0.79 ± 0.35	0.90 ± 0.32
VSBK I	67.4 ± 6.7	2.8 ± 0.3	1.3 ± 0.8	0.05 ± 0.03	0.06 ± 0.04	0.002 ± 0.002	0.74 ± 0.36	0.09 ± 0.09
VSBK V	21.6 ± 2.7	1.6 ± 0.2	1.3 ± 0.7	0.09 ± 0.05	0.01 ± 0.006	0.001 ± 0.0004	1.00 ± 0.40	1.00 ± 0.78
DDK	78.6[1] ± –	13.2 ± –	3.0 ± 0.5	0.50 ± 0.08	1.1 ± 0.4	0.19 ± 0.07	0.74 ± 0.35	0.73 ± 0.31
TK	29.6 ± 4.1	4.5 ± 0.6	1.6 ± 1.8	0.24 ± 0.27	0.01 ± 0.01	0.001 ± 0.001	0.97 ± 0.39	1.00 ± 0.52

[1] The CO sensor overranged in 2 of 3 tests and the result here is likely a low estimate of the CO emission factor.

Table 4.5: CO_2 emission factors in EF_{fuel}, EF_{energy}, and $EF_{kgbrick}$.

KILN	**CO_2 EF**		
	EF_{fuel}	EF_{energy}	$EF_{kgbrick}$
BTK 1	2123 ± 3.7	108.2 ± 0.2	158 ± 0.3
BTK 2	2597 ± 8.2	89.1 ± 0.3	100 ± 0.3
BTK 3	1963 ± 2.8	86.8 ± 0.1	95.8 ± 0.1
NDZ 1	1965 ± 1.6	96 ± 0.1	116.3 ± 0.1
NDZ 2	1976 ± 2.1	99.4 ± 0.1	101.2 ± 0.1
NDZ 3	2099 ± 3.1	102.7 ± 0.2	104.3 ± 0.2
FDZ 1	2104 ± 7.9	88.1 ± 0.3	90.5 ± 0.3
FDZ 2	1941 ± 7.4	98.4 ± 0.4	109.1 ± 0.4
FDZ 3	1831 ± 2.7	99.6 ± 0.1	94.2 ± 0.1
VSBK I	1889 ± 10.5	83 ± 0.5	78.3 ± 0.4
VSBK V	820 ± 4.2	110.4 ± 0.6	60 ± 0.3
DDK	1613 ± –	93.3 ± –	271.1 ± –
TK	1075 ± 6.4	111.2 ± 0.7	163 ± 1

Table 4.6: Organic carbon emission factors in EF_{fuel}, EF_{energy}, $EF_{kgbrick}$.

KILN	OC EF		
	$\mathbf{EF_{fuel}}$	$\mathbf{EF_{energy}}$	$\mathbf{EF_{kgbrick}}$
BTK 1	0.15 ± 0.06	0.008 ± 0.003	0.011 ± 0.004
BTK 2	0.11 ± 0.05	0.004 ± 0.002	0.004 ± 0.002
BTK 3	0.1 ± 0.04	0.004 ± 0.002	0.005 ± 0.002
NDZ 1	0.24 ± 0.3	0.012 ± 0.015	0.014 ± 0.018
NDZ 2	0 ± 0	0 ± 0	0 ± 0
NDZ 3	0.02 ± 0.02	0.001 ± 0.001	0.001 ± 0.001
FDZ 1	0.29 ± 0.33	0.012 ± 0.014	0.012 ± 0.014
FDZ 2	0.04 ± 0.03	0.002 ± 0.002	0.002 ± 0.002
FDZ 3	0 ± 0	0 ± 0	0 ± 0
VSBK I	0.69 ± 0.35	0.03 ± 0.015	0.029 ± 0.015
VSBK V	0 ± 0	0 ± 0	0 ± 0
DDK	0.41 ± 0.22	0.024 ± 0.013	0.069 ± 0.038
TK	0 ± 0	0 ± 0	0 ± 0

Table 4.7: Optical emission factors for absorption and scattering in EF_{fuel}, EF_{energy}, $EF_{kgbrick}$.

KILN	Absorption			Scattering		
	g/kg fuel	**g/MJ**	**g/kg brick**	**g/kg fuel**	**g/MJ**	**g/kg brick**
BTK 1	6.4 ± 2.8	0.33 ± 0.14	0.48 ± 0.21	17 ± 1.81	0.87 ± 0.09	1.26 ± 0.13
BTK 2	2.11 ± 0.13	0.07 ± 0	0.08 ± 0.01	5.21 ± 3.03	0.18 ± 0.1	0.2 ± 0.12
BTK 3	4.23 ± 0.27	0.19 ± 0.01	0.21 ± 0.01	13.28 ± 0.9	0.59 ± 0.04	0.65 ± 0.04
NDZ 1	1.68 ± 0.74	0.08 ± 0.04	0.1 ± 0.04	34.17 ± 7.64	1.67 ± 0.37	2.02 ± 0.45
NDZ 2				0.44 ± 0.39	0.02 ± 0.02	0.02 ± 0.02
NDZ 3				5.49 ± 1.13	0.27 ± 0.06	0.27 ± 0.06
FDZ 1	2.45 ± 1.05	0.1 ± 0.04	0.11 ± 0.05	3.81 ± 1.74	0.16 ± 0.07	0.16 ± 0.07
FDZ 2	0.65 ± 0.16	0.03 ± 0.01	0.04 ± 0.01	3.58 ± 0.69	0.18 ± 0.04	0.2 ± 0.04
FDZ 3	0.53 ± 0.23	0.03 ± 0.01	0.03 ± 0.01	2.47 ± 1.21	0.13 ± 0.07	0.13 ± 0.06
VSBK I	1.15 ± 0.56	0.05 ± 0.02	0.05 ± 0.02	6.26 ± 5.89	0.28 ± 0.26	0.26 ± 0.24
VSBK V	0.02 ± 0.02	0 ± 0	0 ± 0	12.44 ± 6.08	1.68 ± 0.82	0.91 ± 0.44
DDK	3.97 ± 2.53	0.23 ± 0.15	0.67 ± 0.43	11.88 ± 4.09	0.69 ± 0.24	2 ± 0.69
TK	0.03 ± 0.03	0 ± 0	0 ± 0	1.03 ± 1.03	0.11 ± 0.11	0.16 ± 0.16

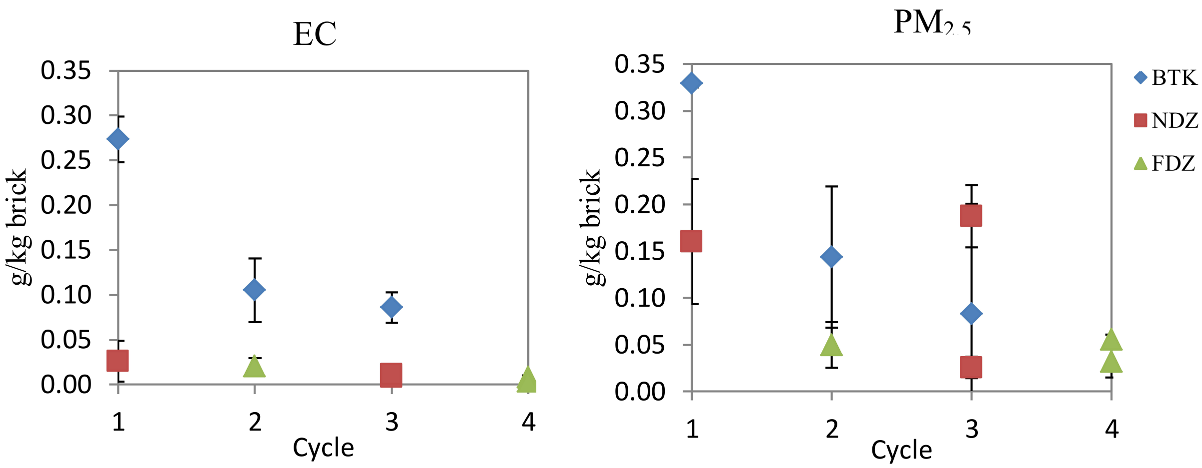


Figure 4.2: Emissions of $PM_{2.5}$ and EC from BTK and zig-zag kilns are higher earlier in the season, in the start-up phase of kiln operation. On the x-axis, the number indicates the operation cycle when the measurement was taken.

to completely combust to CO_2. FDZ, but not NDZ kilns, had statistically lower EF_{fuel} and $EF_{kgbrick}$ of $PM_{2.5}$ ($p < 0.03$) compared to the BTK.

Some of the variability within the same kiln type can be explained by changes in the kiln itself during the season, measured in terms of operation cycles. $PM_{2.5}$ and EC emissions were generally higher near the beginning of the operation season, and lower near the end (Figure 4.2). NDZ1 is a high emitter relative to NDZ2, but it is much lower than BTK1 measured during the same cycle. Likewise, BTK2 is a lower emitter than BTK1, but FDZ1 is lower yet at the same point in the season. NDZ3 is an exception, possibly due to the high sawdust content of the fuel. Overall averages from FDZ kilns were lower than BTK and NDZ, but may have a low bias because measurements were taken later in the season. Similar trends were found in energy consumed per brick, but not in SSA or EC/TC ratios, suggesting that the type of particles emitted is not influenced by the operation cycle.

4.2.3 Improved kilns: tunnel and VSBKs

The tunnel and VSBKs were expected to be low emitting kilns and usually had lower emission factors than the most common kilns in South Asia (BTK and downdraft). The VSBK had a lower EF_{fuel} for $PM_{2.5}$ than the BTK ($p = 0.03$) and both the VSBK and tunnel kiln had statistically lower emission factors of EC than the BTK ($p < 0.006$ and $p < 0.005$, respectively). The Indian VSBK produced the lowest EC/TC (0.09 ± 0.09), compared to ratios above 0.65 for all other kilns. CO_2 emissions in $EF_{kgbrick}$ from the VSBKs were lower than all other kiln types, partly because the production energy (MJ/kgbrick) was lowest in the VSBKs.

Unexpectedly, emissions from the tunnel and VSBK kilns were sometimes greater than those of zig-zag kilns. These improved kilns had higher EF_{fuel} and $EF_{kgbrick}$ of CO than the NDZs ($p < 0.006$ and $p < 0.03$, respectively) and were higher emitters of $PM_{2.5}$ than the FDZs, although the differences were not statistically significant. The combustion in kilns that use internal fuels is fundamentally different; limited oxygen is available at the fuel surface causing increased production of CO and preventing flaming combustion that produces EC. The effects of kiln type and internal fuel cannot be separated. Unlike other kilns, the emissions at the tunnel kiln included both brick drying and firing. The tunnel kiln in this study was a higher emitter than coal tunnel kilns in the US, particularly for CO which was 10 times higher [45].

CO emissions were significantly different for the two VSBKs. The Indian VSBK had the highest CO EF_{fuel} of any kiln, while the Vietnamese VSBK was similar to the BTK and Zig-zag kilns. This variation between the VSBKs disappears when the CO emissions are compared in terms of EF_{energy} because of the low energy fuel used in the VSBK in Vietnam (7.4 MJ per kg fuel) compared to India (22.7 MJ per kg fuel). Other work has reported CO emissions in Vietnamese VSBKs that are higher than either VSBK measured in this study [25]. The causes of high CO emissions should be explored, especially because the VSBK has been proposed as a replacement technology in India.

4.2.4 Emission variability due to fuel feeding

Fuel-feeding caused variability in flue gas concentrations. In the BTKs, NDZs, and first-cycle FDZs, scattering and absorption concentrations rose and fell along with CO and CO_2, increasing soon after fuel feeding and then decreasing after feeding had subsided. CO was correlated with absorption and CO_2 ($R^2 > 0.5$ and 0.4, respectively) (R^2 values in Table 4.8). Peaks in the NDZ kiln emissions had the smallest magnitude. In FDZ kilns in the final cycle, particle scattering had the opposite behavior and the scattering concentrations tended to peak after fuel feeding had subsided).

Table 4.8: R^2 values of three minute real-time concentration data.

KILN	**CO2 and CO**	**CO2 and Scattering**	**CO and Scattering**	**CO2 and Absorption**	**CO and Absorption**	**Scattering and Absorption**	**SSA and CE**
BTK 1	0.95	0.6	0.66	0.46	0.57	0.9	0.01
BTK 2	0.45	0.02	<0.01	0.07	0.52	<0.01	0.55
BTK 3	0.48	<0.01	0.4	0.15	0.8	0.71	0.13
NDZ 1	0.46	0.13	0.12	0.47	0.59	0	0.04
NDZ 2	0.83	0.57	0.34	–	–	–	–
NDZ 3	0.59	0.26	0.49	–	–	–	–
FDZ 1	0.48	0.12	0.51	0.15	0.53	0.92	<0.01
FDZ 2	0.61	0.17	0.01	0.66	0.54	0.14	<0.01
FDZ 3	0.76	0.34	0.41	0.13	0.28	<0.01	0.15
VSBK I	0.35	0.04	<0.01	0.06	0.02	0.81	0.1
VSBK V	0.84	0.67	0.64	<0.01	0.04	0.06	<0.01
DDK	0.12	0.05	0.77	0.03	0.02	0.01	0.25
TK	0.69	0.2	0.04	0.25	0.23	0.18	0.03

Real-time emission variability

Real-time measurements demonstrate the emission variability within a kiln, as summarized for one-minute averages in the box plots in Figure 4.3. Shorter bars indicate lower variability and steadier emissions. There is more confidence that the measured results captured the average in these tests, than those with a wide distribution. The highest variability was observed in the downdraft kiln, likely due to unattended combustion.

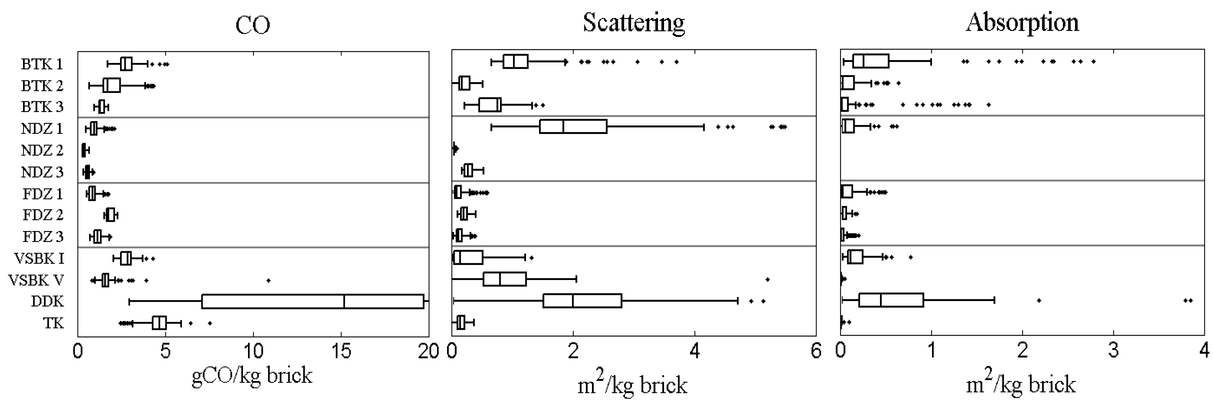


Figure 4.3: Box-and-whisker plots of one minute averages centered on the average value for CO, scattering, and absorption emission factors in $EF_{kgbrick}$.

Scattering emissions from kilns measured in the first cycle of operation (BTK1 and NDZ1) were less consistent than other BTK and Zig-zag kilns and were more left-skewed, with the average influenced by a few high emission events. The FDZs maintained low particle scattering and absorption emissions throughout the combustion, while the VSBKs were more variable.

Zig-zag kilns were the lowest emitting kilns measured in this study, but a clear distinction cannot be made between the FDZ and the NDZ kilns. The highest performing individual kiln in terms of CO and particle emissions was NDZ2, but not all kilns of this type had equally low and steady emissions. Further studies should investigate operational factors that contribute to the observed differences in emissions.

4.2.5 South Asian emissions and mitigation opportunities

Production of an estimated 260 billion bricks in South Asia each year emits approximately 120 ± 24 Tg CO2, 2.5 ± 0.6 Tg CO, 0.19 ± 0.17 Tg $PM_{2.5}$, 0.12 ± 0.7 Tg EC, and 0.02 ± 0.01 Tg OC based on this study (see Table 4.9 for emissions from individual kiln types). $PM_{2.5}$ emissions are of similar magnitude to transportation emissions (0.26 Tg) in South Asia, but much lower than residential combustion (2.6 Tg) [53]. Compared with emission estimates used by UNEP, which were approximated without direct measurements of South Asian brick kilns, for EC, OC and $PM_{2.5}$ (0.09, 0.11, and 0.35 Tg yr-1, respectively) [22], the present estimate of EC emissions is greater, and OC and $PM_{2.5}$ are lower due to differences in both emission factors and brick production between the two studies. Production estimates are 200% higher compared to the UNEP report (2005 estimation). Emission factors in this study for $PM_{2.5}$ and EC are lower than those used in UNEP (2011) [22]; BTK $EF_{kgbrick}$ measurements were 35% and 85% lower for EC and $PM_{2.5}$, respectively.

Changes in dominant brick kiln production technologies in South Asia will alter emissions, and thus the radiative balance of the atmosphere. The most likely conversions are of BTK to zig-zag kilns, and of traditional batch kilns to VSBKs because of their similar production scales.

Figure 4.4 shows estimated radiative forcing by one years emissions from South Asian brick production. In order to compare effects of both short-lived and long-lived pollutants on the same scale, forcing is integrated over 100 years, as is common in emission trading schemes. Error bars indicate the uncertainty in radiative effect. To emphasize the difference between immediate and long-term effects, the figure separates forcing

Table 4.9: South Asian brick production estimates and emissions by kiln type in megagrams per year.

Kiln type	**% of brick production**	**N (# of bricks/year)**	**Mg EC**	**Mg OC**	**Mg SO_2**	**Mg CO**	**Mg CO_2**	**Mg $PM_{2.5}$**
BTK	70%	1.8x1011	78,653	3,572	338,324	1,163,494	64,873,673	93,704
Zigzag	3%	7.9x109	229	109	2,946	22,038	2,361,004	1,424
VSBK	2%	5.2x109	23	217	8,852	32,973	1,042,449	1,077
Trad	25%	6.5101	36,133	13,017	3	1,359,127	51,096,985	91,895
Tunnel	0%	0	0	0	0	0	0	0
Total		**2.6x1011**	**115,039**	**16,915**	**350,125**	**2,577,631**	**119,374,110**	**188,100**

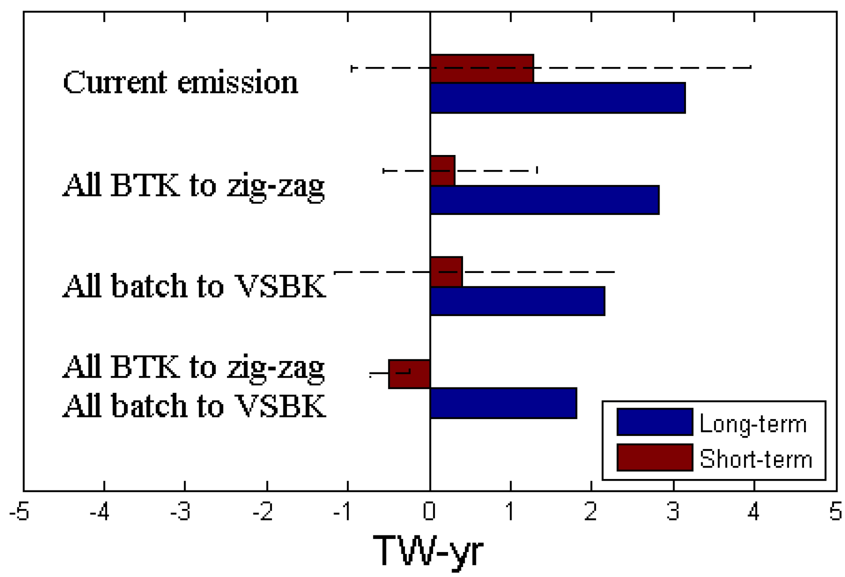


Figure 4.4: Radiative effect of South Asian kilns due to one year of current brick production, for three kiln conversion scenarios at the same production rate. Forcing is integrated over 100 years after emission. Short-term forcing occurs in less than one year, while long-term forcing is the remainder. Error bars represent the uncertainty in the radiative effects only; uncertainty in emission factors is not included.

that occurs in the first year after emission, mainly attributable to aerosols, from forcing by longer-lived species due to greenhouse gases. Because the effects are concentrated around South Asia, the figure presents total forcing in TW rather than a value averaged over the entire globe in W m^{-2}. For comparison, passenger cars in the United States produce about 5 TW-yr of integrated forcing each year. The figure shows that the central estimate of short-lived forcing is about one-half of long-lived forcing, despite the fact that all the short-lived forcing occurs within the first year after emission.

Hypothetical converted scenarios are also shown: all current brick production in BTKs is converted to zig-zag kilns, and all traditional kilns are converted to VSBKs. Currently, forcing from South Asian brick production is positive (warming) and primarily attributable to traditional kilns and BTKs. A 100% conversion of all BTKs to zig-zag would result in a 60% reduction in positive forcing due to short-term forcers, a reduction of 0.85 TW-yr with a 90% uncertainty range of -0.56 to +2.5 TW-yr, and a 10% reduction due to long-term forcers. Converting traditional kilns to VSBKs would reduce short-term forcing by two-thirds (0.42 TW-yr with a range of -0.42 to +1.1 TW-yr); and long-term forcing by about one-third. After conversion of both types of kilns, short-term brick emissions would likely have a cooling effect, largely due to sulfur, and the total short-term forcing would be reduced by 70% (1.9 TW-yr with an uncertainty range of -0.15 to +4.4 Tw-yr). Reductions to the degree shown here would most likely require changes to current regulations.

Chapter 5

Summary

Source emissions measurements were conducted of brick production and household stoves in Asia. This study compared the emission factors and aerosol characteristics from different combustion devices and fuels in these two sectors. Emissions from seventy heating and cooking stoves in Tibet and Nepal and thirteen brick kilns in South Asia were tested to quantify aerosol and gaseous pollutant emissions, including particulate matter ($PM_{2.5}$), carbon monoxide (CO), carbonaceous particles (elemental and organic carbon), and optical scattering and absorption. In addition, a small industry pilot study was conducted of emissions from a restaurant, candy making operation, and two pottery kilns. There are few previous emission measurements in these sectors. This is the first study of black carbon in South Asian brick kilns, the first emission measurements of Nepalese small industries and Tibetan stoves, and the first set of emission measurements considering the diversity of fuel mixtures in Nepal.

Household biomass combustion was compared by stove type and fuel combination. Stoves measured in Nepal emitted more black carbon when sugarcane was used in the fuel mixture. Household biomass emission measurements indicate that chimney stoves had higher combustion efficiency and lower emissions than non-chimney stoves, in Tibet. Wood chimney stoves produced significantly less $PM_{2.5}$ and CO compared to dung stoves in Tibet. Overall, Tibetan stoves had higher emission factors compared to stoves in Nepal or Honduras. Straw combustion for heating in Nepal produced particle emission factors that were over five times greater than stoves in the same region.

Small industry combustion measurements indicate that the industrial stoves, restaurant and candy making, have similar emission factor magnitudes and particle properties to household stoves in Nepal. Emissions from pottery kilns varied depending on kiln type. A traditional straw kiln had high carbon monoxide emission factors and almost no elemental carbon emissions (5% of $PM_{2.5}$). Conversely, the wood pottery kiln had the highest percentage of elemental carbon (78%) compared to other small industries or household stoves (22%).

Measurements in the exhaust of six brick kiln technologies demonstrate differences in overall emission profiles and relative climate warming resulting from kiln design and fuel choice. Emission factors differed between kiln types, in some cases by an order of magnitude. The kilns currently dominating the sector had the highest emission factors of $PM_{2.5}$ and light absorbing carbon, while improved Vertical Shaft and Tunnel kilns were lower emitters. An improved version of the most common technology in the region, the zig-zag kiln, was among the lowest emitting kilns in $PM_{2.5}$, CO, and light absorbing carbon. Emission factors measured here are lower than those currently used in emission inventories as inputs to global climate models;

85% lower ($PM_{2.5}$) and 35% lower for elemental carbon)for the most common kiln in the region, yet the ratio of elemental carbon to total carbon was higher than previously estimated (0.96 compared to 0.47). Total annual estimated emissions from the brick industry are 120 Tg CO^2, 2.5 Tg CO, 0.19 Tg $PM_{2.5}$, and 0.12 Tg EC.

5.1 Recommendations

1. Straw used for heating in Nepal had very high particle emission factors. Future work should investigate the magnitude and seasonality of this practice to determine the significance on regional pollution. From a health perspective, exposure monitoring should be done to determine the health risks to the population.

2. In this study there were significant differences in emission factors between the two stove measurement regions. Further work to understand what contributes to the differences could help researchers make predictions of emission factors in unmeasured regions. For example, the same stove could be brought to each measurement location, to isolate the effect of atmospheric conditions on emissions. Identical fuel could also be taken to different regions to help isolate the emission characteristics attributable to stove design or operation.

3. The brick kiln measurements were variable within kilns. Continuous real-time monitoring at a kiln of CO_2, CO and particle scattering would show how much emissions vary over the day and the season, and identify when the greatest emissions occur.

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